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PROPOSAL TO STUDY CHANNELING AT FERMILAB

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SUMMARY

Channeling, the behavior of charged particles moving through the planes and rows of aligned single crystals, has been studied with great success in connection with many solid state and nuclear processes at low energies. We propose to study channeling at Fermilab energies where the dechanneling lengths are so long that thick single crystals may be used and many different particles, including negative particles other than electrons, are available. Both of these factors permit significant extensions of channeling experiments.

The experimental apparatus will consist of a single crystal and its associated goniometer along with position detectors fore and aft of the goniometer to measure the trajectories of the particles. A goniometer and associated germanium single crystals are available from Bell Laboratory. The system has already been calibrated at Van de Graaff and AGS energies. The high precision drift plane system presently in operation at Fermilab for the kaon form factor experiment (E-456) will be used to measure particle directions before and after the single crystal. Two hundred and fifty hours of beam time are requested. We believe it is desirable to schedule this test of channeling in conjunction with the running of the form factor experiment, in part to provide a calibration of the drift chamber system.

INTRODUCTION

This is a proposal for a parenthetical experiment. It has to do with the steering of charged particles of energy up to 200 GeV by rows or planes of atoms in a single crystal. This steering effect, called particle channeling,[1] has been much studied and is well described theoretically for positive particles at energies up to 50 MeV.[2] (Appendix I contains a discussion of some applications of channeling.) Similar effects are clearly predicted by the theory up to the highest energies. Indeed, the effects should get stronger as the energy is increased since the competing multiple scattering effects scale as E^{-1}, whereas the steering effect (in angular extent) is predicted to scale as $E^{-\frac{1}{2}}$, so that at Fermilab energies, crystals several mm thick may be used.

Recent experimenters at CERN[3,4] and BNL[5] have shown channeling is operative at ~ 1.1 GeV/c and ~4 GeV/c respectively. In these experiments, the crystals show increased transmission of particles along the planes and axes of a crystal, leading to peaks in a scatter plot of incident projected angles. The widths of these angular enhancements are directly related to the so-called critical angles for channeling. The axial critical angle for singly charged relativistic positive particles is given by

$$\psi_c = 2\sqrt{\frac{Ze^2}{p\beta cd}} \tag{1}$$

where d is equal to the spacing of the atoms along the atomic row.

The CERN experiment shows, for positive particles, results about as predicted by the classical theory. (See fig. 1) The CERN experiment has also measured energy deposits in a single crystal as a function of particle incident angle. The experimental agreement is good enough to allow the effect to be applied in some important tests of the theory of energy loss and straggling of positive particles in solids (fig. 2) and to suggest possibly useful applications as a collimating element in ultra-high energy physics. (See Apendix II for a discussion of the energy loss measurements.) The results encourage us to look even higher in energy where competing processes should become even less important, where similar or other applications could be useful and where the limits of the classical theory can be further tested.

For negative particles, the situation is less clear and quite intriguing. The CERN results for 1.1 GeV/c π^- shows a result not predicted by the theory. In the angular distribution of particles transmitted through a crystal, the theory predicts a deep and narrow minimum. The experiment shows a prominent and narrow maximum surrounded by a broad minimum (fig. 3); whereas, the BNL results at 4 GeV/c indicate (with less statistical accuracy) a narrow minimum (fig. 4). Admittedly, the theory is not so well worked out as for positive particles. This is in part due to the paucity of experimental data for negative particles except for low energy electrons (< 1 MeV) where diffraction effects begin to interfere. Such measurements of high energy electrons as exist

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appear to be in better qualitative agreement with the BNL than the CERN results. Clearly, some additional and systematic experiments are called for.

By measuring the transmission as a function of incident angles at Fermilab energies, we will be able to observe the behavior of channeling at very high energies, extend channeling measurements to several different negative particles, and test the energy dependence of dechanneling lengths at high energies by using crystals of different thicknesses. The experiment will also provide some of the most challenging tests of the developing technologies in very high resolution drift planes and large single crystals.

The proposed experiment represents a diversion for Fermilab intellectually as well as physically. For this we do not apologize. Indeed, we regard this as a strength. We believe, however, that this experiment can be carried out efficiently (perhaps even parasitically) using existing equipment and personnel with a minimum cost or distraction to existing or proposed Fermilab programs. If there is room at Fermilab for such diversion, we elicit serious consideration of this proposal.

CHANNELING MEASUREMENTS

There are two modes for carrying out channeling experiments. One is to use a beam with sufficient divergence so that it includes the entire range of angles of interest (several hundred microradians). Drift chambers can then be used to define the particle direction before and after the crystal and hence to look at the probability for particles to pass through the crystal undeflected as a function of the direction of incidence. This method provides the most convenient and informative survey of the channeling probability, angular extent and other factors. Only a fraction of the particles incident will meet the necessary angular criteria to be channeled.

The other mode which could be used in subsequent measurements of, for example, energy loss or beam collimation makes more efficient use of the beam. It involves use of a parallel beam (preferably with divergence less than the channeling critical angle involved) and precise alignment of the crystal with the incident beam direction. In this mode a large fraction, greater than half, of the particles could be captured into channeling trajectories. A parallel tune of this sort can be implemented with the M1 beam in the Meson Laboratory.

BEAM CONDITIONS

The M1 beam in the Meson Laboratory has a sufficient intensity of all long-lived charged particles with the possible exception of electrons. (Tagged electrons are present at around 0.1% and muons are present at a level of less than one percent at 100 GeV.) We propose to run both positive and negative particles for four different beam momenta, from the highest possible momentum with the beam down to the lowest momentum with the hope of being able to match on to channeling experiments now underway at Brookhaven and planned at CERN. It is estimated that the primary time requirement would be to set up the apparatus and trigger. At present, neither of these seem to be particularly time consuming. We estimate one eight-hour shift is necessary to run each momentum sign, provided the same sign and momentum set are already established. We propose to run with several different single crystal thicknesses at the lowest and highest momenta. This proposal will require 250 hours of beam time.

APPARATUS

For channeling studies, it is important to use crystals of sufficient perfection to observe the desired effects. The small critical angles for channeling encountered at high momenta (expected to be on the order of 70 microradians at 100 GeV/c) put strong restrictions on the amount of mosaic spread which can be tolerated. (Mosaic spread is a term which is used for localized variations in crystal orientation due to slip planes, dislocations and other crystal defects.) Dislocation-free germanium crystals have been chosen as the best available candidates for high energy channeling studies on the basis of anomalous X-ray transmission and lower energy particle channeling measurements. The Brookhaven experiment has been performed with such crystals. They are also expected to be suitable at Fermilab energies.

A special high precision goniometer is available for crystal orientation. This goniometer has a measured precision of 50 microradians in scanning angles and a reproducibility of 170 microradians in setting absolute angles using a remote digital angle encoder and readout and control system. The goniometer has been used in the experiments at Brookhaven and would be moved to Fermilab. Note that in the mode proposed for this experiment, the goniometer is used only to position the crystal initially. The germanium crystals have already been pre-oriented and tested at MeV energies with the Tandem Van de Graaff at Brookhaven and at GeV energies with the AGS.

The foundation of an apparatus for channeling studies exists in the M1 beam in the Meson Laboratory. The apparatus for E-456, kaon form factor, employs low multiple scattering drift planes similar to those developed by Charpak and Sauli for the CERN channeling studies. These planes have spatial resolutions of 60 microns rms.[6] Within the critical angle for channeling there is effectively no multiple scattering by the single crystals so that the planes near the crystal are the sole contribution to multiple scattering in the angle measurement. The measurement system will consist of three-high resolution, thin x, y plane pairs - one thirty meters upstream of the single crystal goniometer, one at the single crystal and one twelve meters downstream. The layout for the angle measuring system is shown in Figure 5.

Figure 6 shows the expected half angle at half maximum for axial channeling in the <110> direction in germanium as a function of energy. The curve has been extrapolated from the CERN measurements at 1.35 GeV/c, and as such, is based on an experimental measurement. Note that this angle is smaller than the critical angle given by (1). At 100 GeV/c, the half angle at half maximum is expected to be 35 microradians. Figure 6 also shows the expected resolution for the kaon form factor apparatus with a new drift plane at the center along with the present drift chambers of E-456 for the upstream and downstream measurements. The new center module will have wires with half the diameter used at present and two x and two y measurements rather than four of each. This cuts the radiation length of the center module by five and requires no new technology. For the E-456 plane separation and the new drift plane set in the center, the half angle-half max resolution at 100 GeV/c is 11 microradians. The new center module can be quickly constructed using existing parts that are available in the Dubna group.

Figure 7 illustrates the expected channeling line shape and background at 100 Gev/c extrapolated from the CERN measurements at 1.35 GeV/c. The effect of resolution is also shown. Since the planar channeling angles are expected to be substantially smaller than the axial angles, it is well to strive for high resolution.

The present E-456 system is capable of taking up to 120 events per pulse with drift chambers. Total particle fluxes through the planes can be upwards of a million per pulse. Of course, kaons and antiprotons constitute a minor fraction of these. Statistics comparable to

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the ones obtained in the recent Aarhus-CERN channeling study near 1 GeV/c (Figures 1, 3) can be achieved in about twenty machine pulses.

The necessary goniometer and single crystals are available now and can be moved to the Laboratory and positioned in place with about a week's notice. We believe the kaon form factor scattering apparatus can be converted quickly and relatively easily. We believe it is important that the channeling run be scheduled in conjunction with the form factor experiment running. In a sense, the form factor running will constitute an excellent calibration of the apparatus for the channeling studies. Note that the angular precision requirements for the kaon form factor are similar to those required for channeling so that successful preparation for one experiment assures satisfactory operation for the other. It is anticipated that there will be no substantial additional requirements on the Laboratory beyond use of the beam and the scattering apparatus. We would prefer that the differential Cerenkov counter system be available for particle identification.

A number of the experimenters on the form factor experiment are participating in this proposal. While this experiment is not the dominant interest of the kaon form factor group, we feel that it constitutes an interesting auxiliary experiment.

Appendix I - Applications of Channeling

The experimental and theoretical development of the understanding of charged particle motion in single crystals, channeling, has been enormous in the last decade. In addition, the channeling effect has also been particularly useful for the study of solid state phenomena with important applications in studies of impurity locations in solids, surface structure and catalysis. In nuclear physics it has provided a means for measuring compound nuclear lifetimes in the range 10^{-14} to 10^{-18} seconds. It is also finding increased use for practical applications such as ion implantation. The possible technological applications for this field appear to be nowhere near exhaustion.

There may be practical applications of channeling to high energy experimentation. Solid state detectors are already used in the Fermilab program. These detectors are now cut so that they are not aligned along channeling directions. If energy loss measurements show significant differences for channeled particles, identification signals for channeled and, therefore, highly collimated particles are available by making the crystal a detector. This situation is discussed in Appendix II. Such detectors might also be used for particle identification. Channeling may also be able to be used to devise low multiple scattering devices in certain applications.

Recently, exotic applications of single crystals for studying short-lived particle interactions and lifetimes have been suggested.[7] Studies of conventional channeling offer the first step in seeing if the necessary single crystal technology can be put into application at Fermilab.

Appendix I (cont.)

Tsyganov[8] has also proposed that single crystals could be used for bending and cooling particle beams. A deformation of a single crystal might be used to deflect channeled particles analogous to the way a light pipe guides light. Particle beams moving along channeled trajectories may lose transverse momentum to the lattice so that the transverse motion is damped. Both possibilities are straightforward to test in the experiment proposed here.

Appendix II - Energy Loss Effects at High Energy

In the recent CERN experiments, the ionization energy deposited in a 1 mm thick germanium crystal by transmitted 1.35 GeV/c protons and positive and negative pions was measured. The crystal was itself a detector made by applying rectifying contacts and totally depleting the crystal through its thickness so that electron-hole pairs produced by the transmitted particles could be swept apart and measured. It was found that channeled protons and positive pions had an energy loss about one-third of that of unchanneled particles. For negative pions, no such reduction in energy loss for channeled particles was observed. An apparent slight and unexpected difference in the energy loss between channeled protons and channeled positive pions is not explained but may be due in part to the fact that the protons are not as relativistic as the pions at ~1 GeV/c. Higher energy measurements will clarify this situation. The observed differences in the channeled and unchanneled particle energy loss form the basis for suggested particle identification and collimation applications in high energy physics experiments.

Basic energy loss processes or energy transfer phenomena are of particular interest at ultra high energy since present theories of electronic energy loss are asymptotic; that is, they are strictly valid only in the high energy limit. In some cases, the predictions of different theories differ qualitatively. For example, a recent and widely accepted theory by Dettman[9] predicts that in the high energy limit, channeled particles will have the same energy loss

Appendix II - cont.

as unchanneled particles. On the other hand, an even more recent theory of Golovchenko[10] predicts a difference of about a factor of two. The results support the latter theory but other and even higher energy measurements should be made.

BIBLIOGRAPHY

[1]For reviews see D. S. Gemmell, Rev. Mod. Phys. 46, 129 (1974) and D. V. Morgan, Ed, Channeling (Wiley and Sons, N. Y., 1973).

[2]J. Lindhard, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 34, No. 14 (1965).

[3]O. Fich, A. J. Golvchenko, K. O. Nielsen, E. Uggerhoj, G. Charpak, and F. Sauli, Phys. Let. 57B, 90 (75).

[4]O. Fich, J. A. Golovchenko, K. O. Nielsen, E. Uggerhoj, C. Vraast-Thomsen, G. Charpak, S. Majewski, F. Sauli, and J. P. Ponpon, CERN preprint - 1975 (Submitted to Phys. Rev. Let.)

[5]D. Allen, W. Gibson, D. Gockley, A. Kanofsky, G. Lazo, H. Wegner - Preprint 1975.

[6]T. S. Nigmanov, et al, Fermilab 76/26, March 1976.

[7]R. A. Carrigan, Jr., Phys. Rev. Let. 35, 206 (75). G. W. Temmer, Proceedings of the Kentucky Conference on Low-Medium Mass Nuclei (J. P. Davidson and B. Korn, Eds.), 192 (1973).

[8]E. N. Tsyganov, Fermilab TM 682 (1976).

[9]K. Dettman, Ed S. Datz, B. R. Appleton, C. D. Moak, Atomic Collisions in Solids, (Plenum Press, N. Y., 1975), and K. Dettman and M. T. Robinson, Phys. Rev. B10, 1 (1974).

[10]J. A. Golovchenko and H. Esbensen, Univ. of Aarhus Preprint, submitted to Phys. Rev. A 1975.

Figure 1

Intensity of 1.35 GeV/c π^+ which have been transmitted through a 1 mm thick germanium crystal with less than 0.35 mrad deflection inside the crystal as a function of incidence direction relative to a <110> crystal axis. The solid line is *not a theoretical* curve but is in reasonable agreement with the distribution expected from lower energy (<50 MeV) proton transmission measurements. (From Ref. 4)

Figure 2

Energy loss of 1.2 GeV/c protons scattering less than 0.35 mrad in passing through a 1 mm thick germanium crystal for particles incident parallel to a <110> crystal axis (closed points) and incident in a non-channeled (random) direction (open points). After correction for energy transferred to electrons knocked out of the sample without depositing all of their kinetic energy, the energy loss difference between random particles and those incident along the axis is almost a factor of three. (From Ref. 4)

Figure 3

Intensity of 1.1 GeV/c π^- transmitted through a 1 mm thick germanium crystal with less than 0.7 mrad deflection inside the crystal as a function of the incidence direction relative to a <110> crystal axis. (From Ref. 4)

Figure 4

Intensity of 4 GeV/c π^- transmitted through a 1 cm thick germanium crystal as a function of the incidence direction relative to a <110> crystal axis. In this measurement, the statistical accuracy is very much reduced because the experimental arrangement allowed only one incident particle direction to be investigated at one time in contrast to the use of position sensitive proportional counter or drift chamber planes as in the previous figures or in this proposal. (From Ref. 5)

Figure 5

Proposed system for channeling studies using the kaon form factor apparatus.

Figure 6

Axial channeling for germanium and expected resolution for the kaon form factor apparatus.

Figure 7

Line shape expected at 100 GeV/c for axial channeling in germanium for the <110> direction using the kaon form factor apparatus. The channeled line is extrapolated from Reference 4.

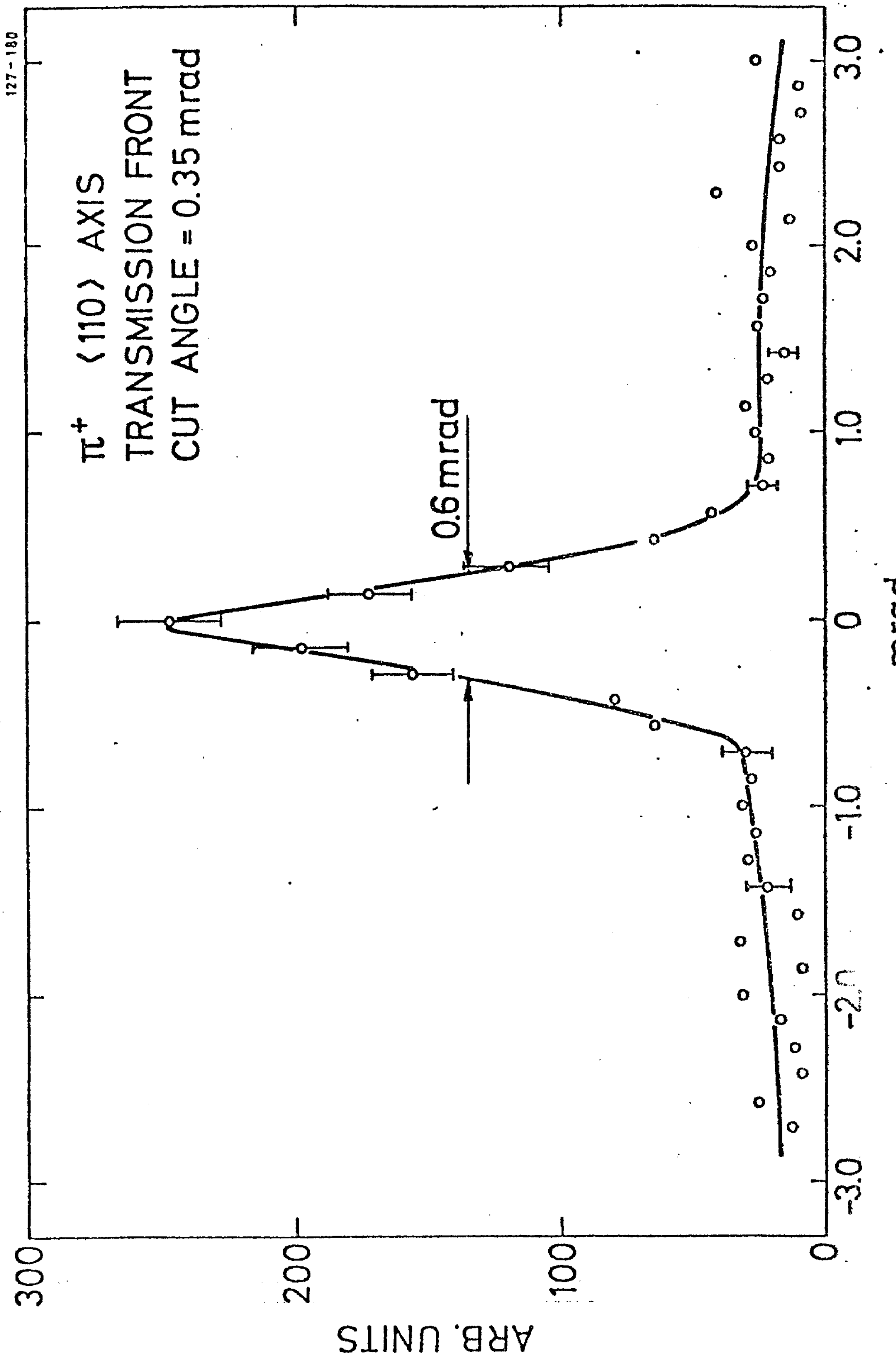


Figure 1 (From Reference 4)

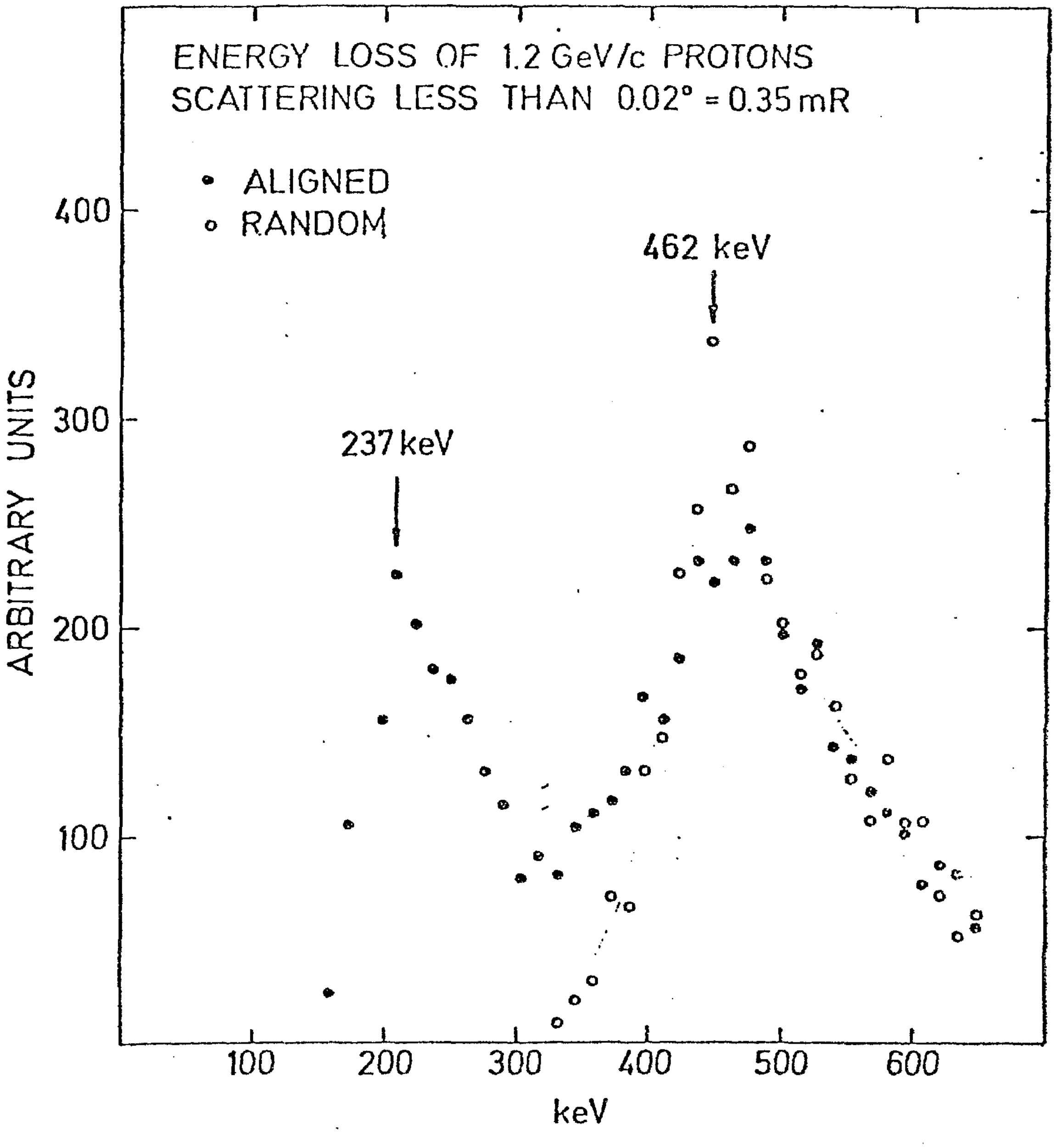


Figure 2 (From Reference 4)

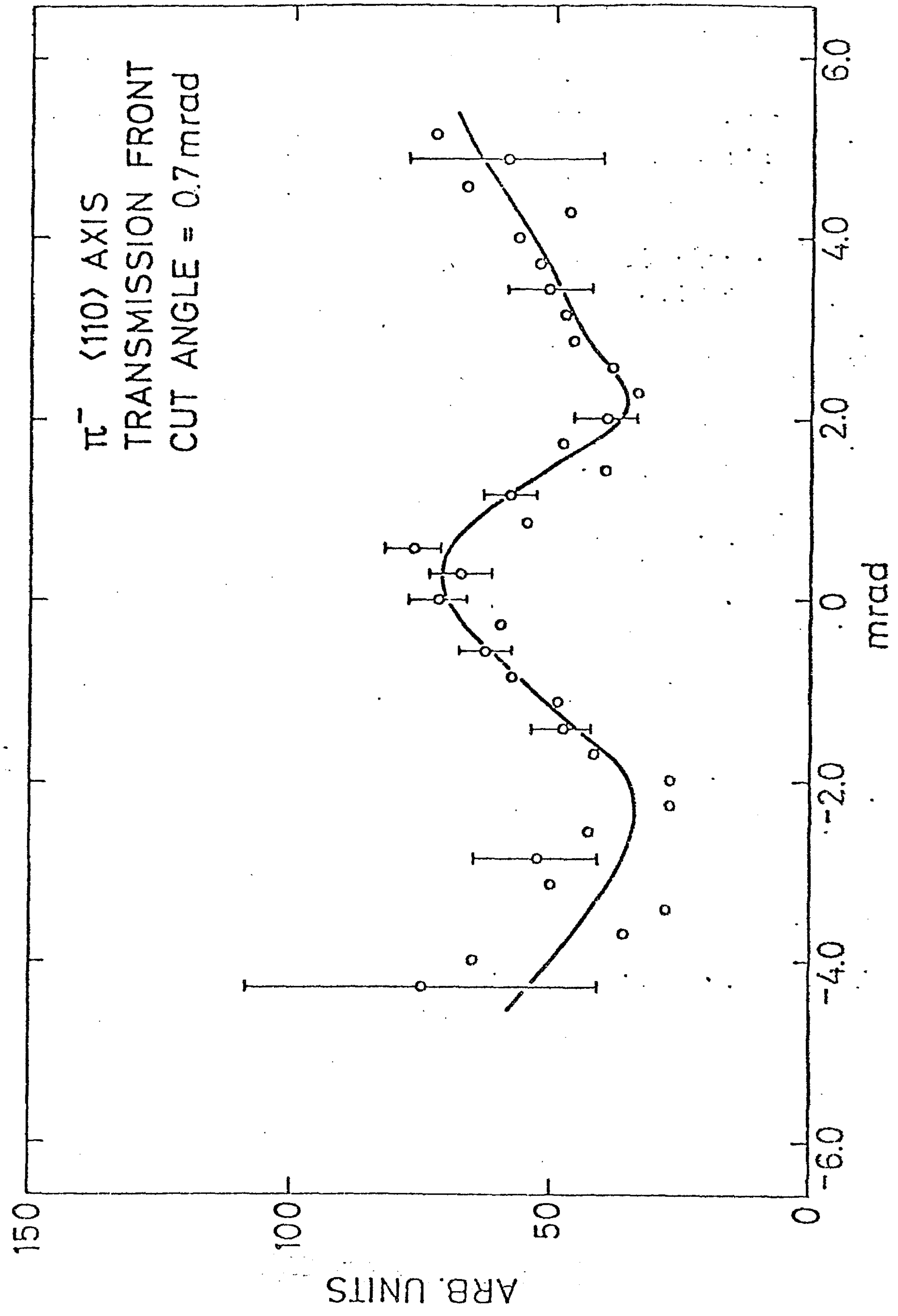
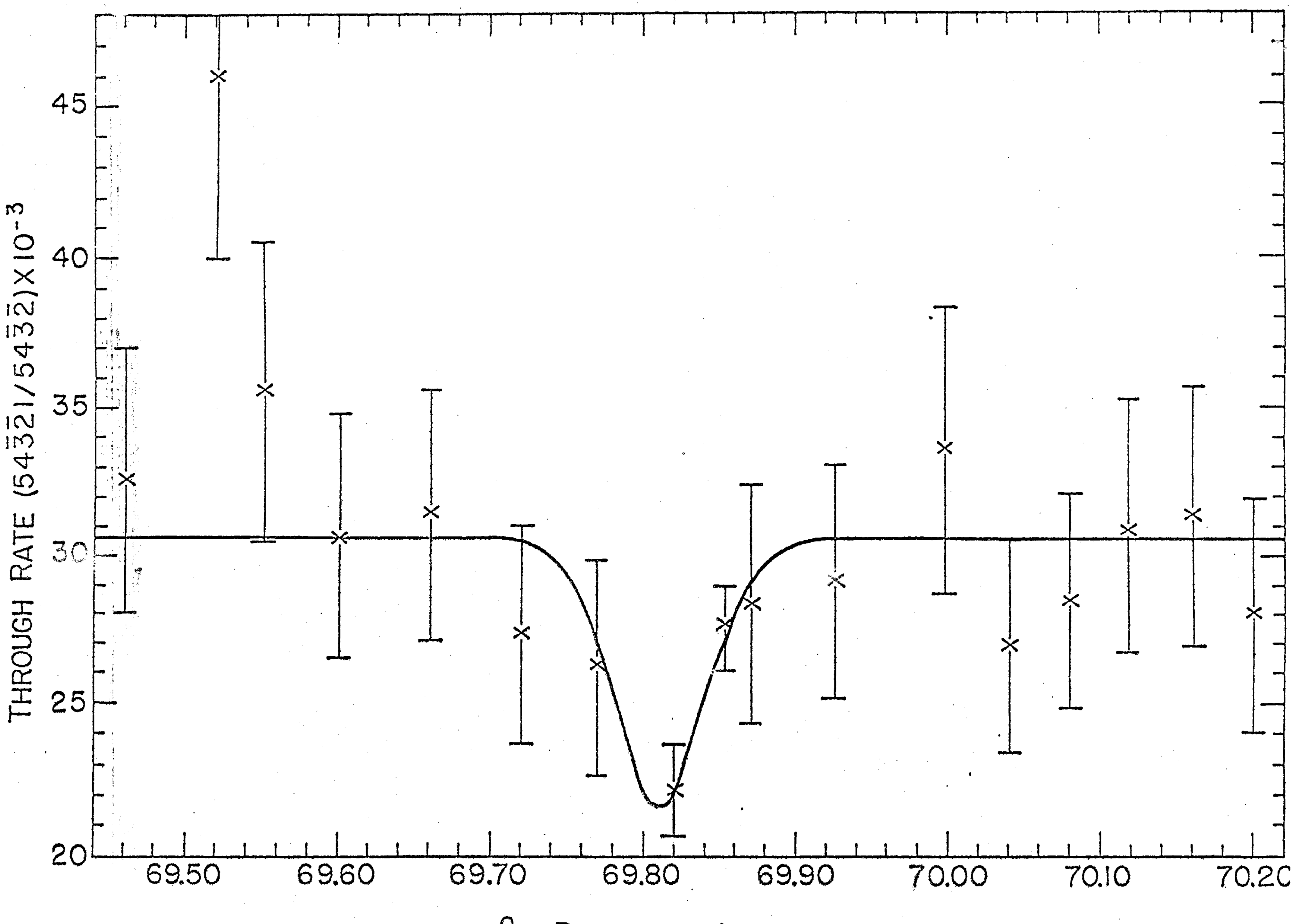


Figure 3 (From Reference 4)



THROUGH RATE $(54\bar{3}\bar{2}1/54\bar{3}\bar{3}\bar{2})\times10^{-3}$
45
40
35
30
25
20
69.50
69.60
69.70
69.80
69.90
70.00
70.10
70.2C
θ - ROTATION ANGLE

Figure 4

PROPOSED SYSTEM FOR CHANNELING STUDIES USING THE KAON FORM FACTOR APPARATUS

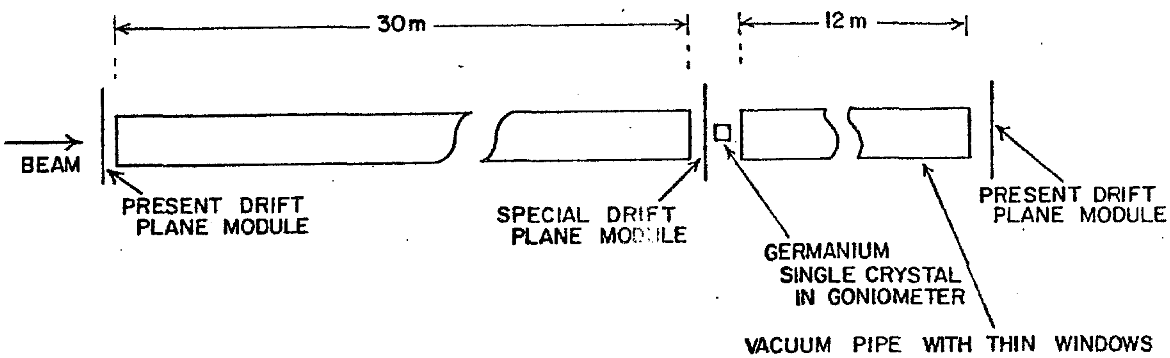


Figure 5

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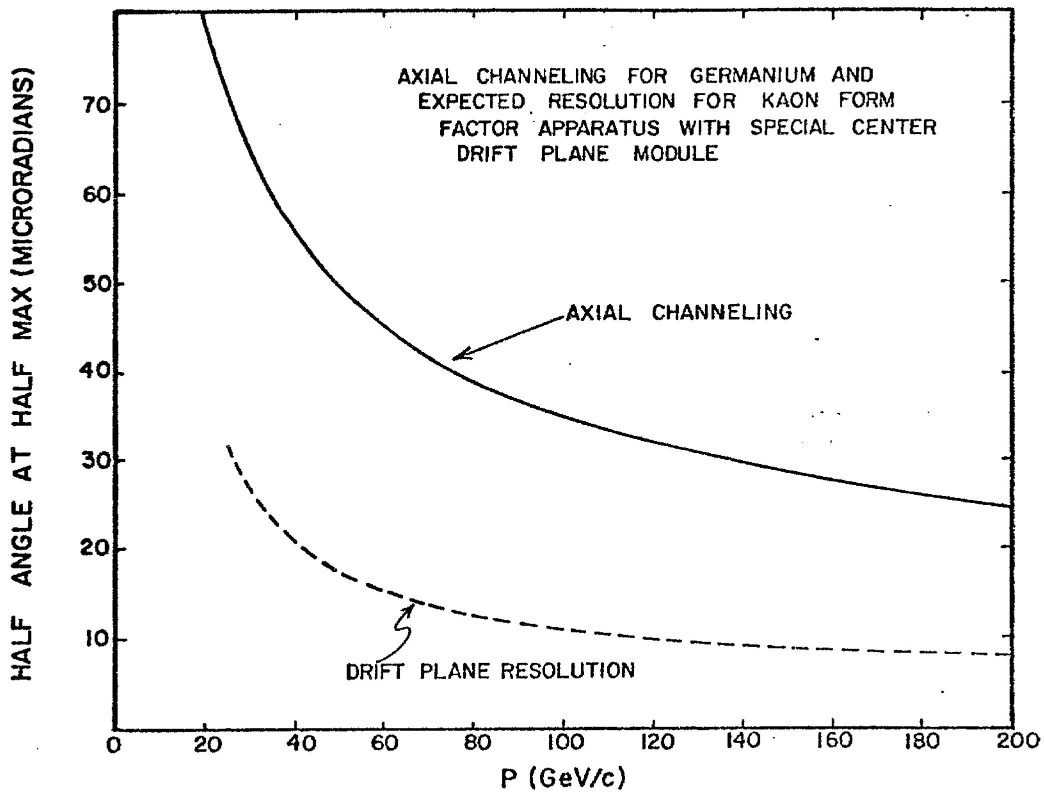

AXIAL CHANNELING FOR GERMANIUM AND EXPECTED RESOLUTION FOR KAON FORM FACTOR APPARATUS WITH SPECIAL CENTER DRIFT PLANE MODULE
AXIAL CHANNELING
DRIFT PLANE RESOLUTION
HALF ANGLE AT HALF MAX (MICRORADIANS)
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
P (GeV/c)

Figure 6

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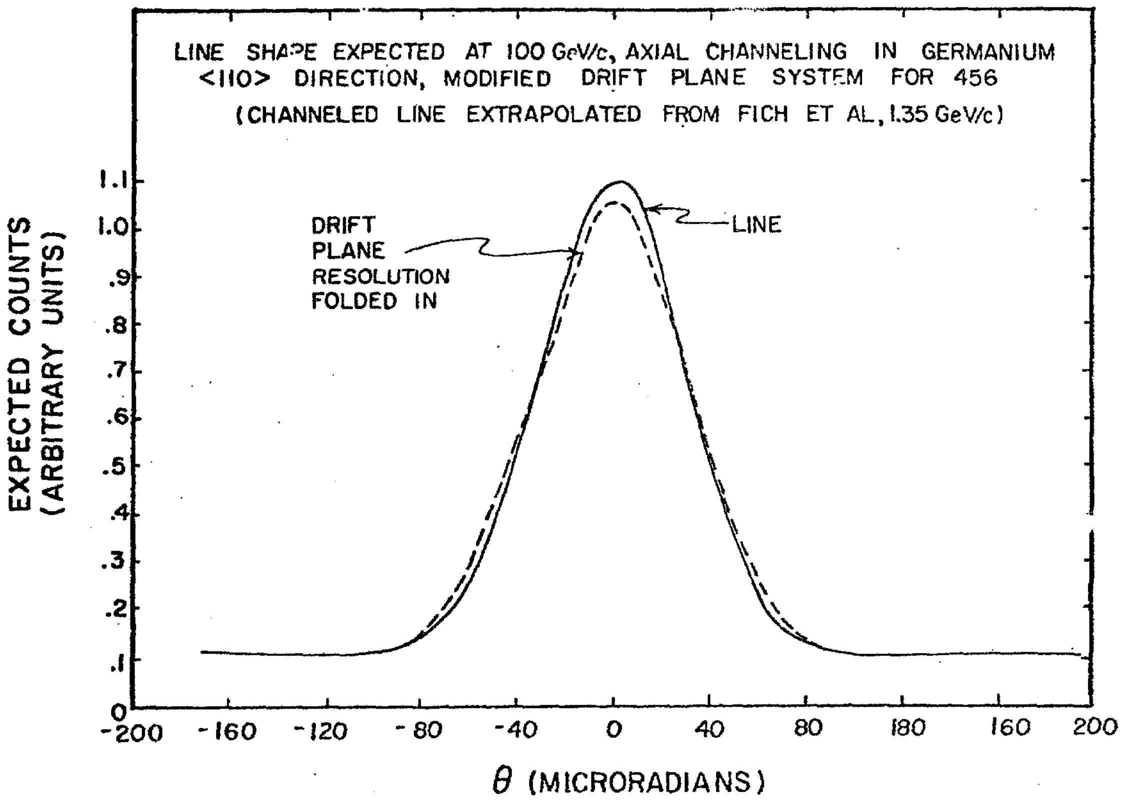

LINE SHAPE EXPECTED AT 100 GeV/c, AXIAL CHANNELING IN GERMANIUM
<110> DIRECTION, MODIFIED DRIFT PLANE SYSTEM FOR 456
(CHANNELED LINE EXTRAPOLATED FROM FICH ET AL, 1.35 GeV/c)
DRIFT PLANE RESOLUTION FOLDED IN
LINE
EXPECTED COUNTS (ARBITRARY UNITS)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
-200
-160
-120
-80
-40
0
40
80
180
160
200
θ (MICRORADIANS)

Figure 7